Generation, Transport and Fate of Surfzone Bubbles

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LONG TERM GOALS

ur long term goal is to develop a tested model of optical properties in the surfzone and adjacent nearshore ocean, including the influence of suspended sediment and bubble population, to assess how optical properties are related to short term events such as individual breaking wave crests, and to determine how wave-driven surfzone circulation influences optical properties just offshore of breaking through seaward transport of fine sediment and small, persistent bubbles.

OBJECTIVES

The ability to make optically-based observations in nearshore waters is strongly influenced by the presence of suspended sediment particles and of bubbles, both of which are present due to the action of breaking waves. Wave breaking is instrumental in injecting large volumes of air into the water column. This air volume subsequently evolves into a distribution of bubble sizes which interact with the fluid turbulence and are advected by the organized flow. Our initial objective is to specify a general framework for bubble dynamics in a sediment laden environment, and to implement this formulation in a wave-resolving model of surfzone processes. Specific objectives in support of this effort include:

1) Develop a multiphase model for the evolution and transport of a bubble size distribution in a turbulent, sediment-laden flow.

2) Utilize a RANS-VOF model to provide information about the spatial and temporal distribution of bubble sources related to breaking wave events.

APPROACH

Our initial approach to the problem is based around incorporating a comprehensive model of bubble physics within a Reynolds-averaged 2D hydrodynamic code. The physics is represented by a multiphase continuum model, using the formalisms described by Drew and Passman (1999). In the present project, we are aiming to implement a model combining a water phase, a bubble phase with multiple bubble size (or, more accurately, mass) bins, and a non-cohesive sediment phase, also

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including multiple size or weight bins. A comprehensive version of the model physics would include full coupling between bubble size bins (fractionation and coalescence), interaction between sediment size classes (hindered settling and effect on turbulence), and interaction between sediment and bubble phases as well as between each of these and the water column. Carrica et al (1999) have provided a detailed model for the bubble/water component. The sediment component would be an elaboration of the two-phase model of Hsu et al (2003) to include multiple grain size bins. Finally, the framework for the bubble/sediment interaction needs development in the context of the present project. In order to get basic aspects of the transport problem implemented and tested first, we are presently running a version of the code with a simplified bubble phase description due to Buscaglia et al (2002), a simple advection-diffusion scheme for the sediment size bins, and no interphase interaction. Our plan is to be concentrating more on the interphase interactions by the end of year one of the project, and to begin specifying and implementing the model in a 3-D version of the code towards the end of the second year, utilizing a LES hydrodynamic model such as the ones described in Christensen (2006) or Lubin et al (2006). Also, we hope to begin collaborative efforts aimed at model verification with other investigators during year 2.

WORK COMPLETED

The three-phase model can be obtained by ensemble averaging the conservation equations for each phase in a multiphase flow, following Buscaglia et al. (2002). Brief descriptions of the treatment of the fluid phase, bubble phase and sediment phase follow

The mixture fluid phase:

Equations for mass and momentum conservation for the spatially averaged fluid phase are given by

$$\nabla \cdot \mathbf{u}_m = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}_m}{\partial t} + \mathbf{u}_m \cdot \nabla \mathbf{u}_m + \frac{1}{\rho_0} \nabla P_m = \frac{1}{\rho_0} \nabla \cdot \left[\mu_T (\nabla \mathbf{u}_m + \nabla^T \mathbf{u}_m) \right] - \frac{\rho_m}{\rho_0} g\mathbf{k} \tag{2}$$

where $\mathbf{u}_m, P_m$ and ρ_m represent the mixture quantities of fluid velocity, pressure and density, respectively. ρ_0 is the so called reference density which has replaced ρ_m in all terms but the gravity term using the Boussinesq approximation. $\mathbf{k}$ is a vertical unit vector. μ_T is the eddy viscosity coefficient which is specified using $k - \varepsilon$ turbulence equations.

The buoyancy force (the last term in (2)) can be evaluated as

$$\frac{\rho_m}{\rho_0} g\mathbf{k} = \left[1 - \alpha_b + \alpha_s (\rho_s / \rho_w - 1) \right] g\mathbf{k} \tag{3}$$

where α_b and α_s are the volume fractions of bubbles and sediment following the definitions in Drew and Passman(1998). ρ_w and ρ_s represent water density and sediment density, respectively.

Bubble phase:

Mass bin i of the bubble population are presently calculated using simple advection-diffusion equations given by

$$\frac{\partial C_b(i)}{\partial t} + \nabla \cdot (C_b(i)\mathbf{u}_g) = \mathbf{S}_c + \nabla \cdot \left(\mathbf{D}_g \nabla C_b(i)\right)$$

(4)

$$\frac{\partial N_b(i)}{\partial t} + \nabla \cdot (N_b(i)\mathbf{u}_g) = \mathbf{S}_n + \nabla \cdot \left(\mathbf{D}_g \nabla N_b(i)\right)$$

(5)

where $C_b(i)$ and $N_b(i)$ represent, respectively, the gas molar concentration and bubble number per unit volume for bubble size i. $\mathbf{u}_g$ is the bubble advection velocity which can be calculated by

$$\mathbf{u}_g = \mathbf{u}_m + w_b(r_b)\mathbf{k}$$

(6)

in which $w_b(r_b)$ is the bubble-slip velocity, assumed only depending on the bubble radius. $\mathbf{S}_c$ and $\mathbf{S}_n$ are source/sink terms associated with inter-phase adjustment of bubble quantities between different component i caused by bubble size changes due to pressure change, bubble-sediment interaction, bubble breakup and coalescence, and are not yet implemented in code. $\mathbf{D}_g$ is the dispersion coefficient associated with the turbulence and bubble-sediment interaction.

As a simple initial approach, the source/sink terms in (4) and (5) can be evaluated based only on bubble size changes due to pressure without taking into account sediment effects, bubble breakup and coalescence.

Sediment phase:

The evolution of the i'th bin of the sediment phase is computed according to

$$\frac{\partial C_s(i)}{\partial t} + \nabla \cdot (C_s(i)\mathbf{u}_s) = \nabla \cdot \left(\mathbf{D}_s \nabla C_s(i)\right)$$

(7)

where $C_s(i)$ is the sediment concentration with a grain size numbered as i. $\mathbf{D}_s$ is the coefficient for sediment dispersion which links to turbulence and bubble-sediment interaction. $\mathbf{u}_s$ is the sediment advection velocity which can be evaluated by

$$\mathbf{u}_s = \mathbf{u}_m - w_s(r_s)\mathbf{k}$$

(8)

in which $w_s(r_s)$ is the sediment particle fall velocity with respect to grain size r_s. A pick-up function is used at the bottom boundary in order to entrain sediment from the sand bed.

Model Implementation:

We use the 2-D VOF model, RIPPLE, as the basic framework for the computational code. The VOF model has been enhanced with several different turbulence closure models such as $k - \varepsilon$ model (Lin and Liu, 1998) and multi-scale LES model (Shi et al., 2004). The governing equations (4) and (5) for the bubble phase and (7) for the sediment phase have been implemented based on the existing Lagrangian tracer subroutines. The connection between the intensity and size spectra of entrained bubbles and turbulence levels in the surfzone is formulated following the previous studies by Terrill et al. (2001) and Garrett et al. (2000), among others.

RESULTS

Preliminary results using the simplified initial model have been obtained for the case of laboratory-scale periodic waves shoaling on a plane beach. Figures 1 and 2 each show results for two of the bubble size bins, with the figures staggered in time to illustrate the evolution of the bubble cloud behind the passing wave crest.

Although the restriction to two dimensions implies a drastic reduction in complexity of the turbulent flow field, several interesting features still emerge in the simulation. First, it is evident that there is an overall spatial patchiness in bubble concentration when measured in terms of distance behind the wave crest. This patchiness is qualitatively consistent with structures seen in laboratory ARGUS imagery of experiments in the Large Wave Flume at OSU (Haller, personal communications). We have not begun the process of determining whether there is quantitative agreement between measured and predicted spatial lengthscales, though.

The numerical results also often show apparently trapped pockets of high bubble phase concentration below the water surface. A closeup of such a region is examined in Figure 3, which illustrates bubble concentration and water phase velocity vectors. It is apparent that organized eddy motions in the model are successfully trapping and concentrating bubbles towards the central vortex axis, as would be expected from the action of centripetal forces on the lighter bubble phase.

IMPACT/APPLICATIONS

The work proposed here would provide a general framework for modeling bubble distribution in the surfzone. The model framework for bubble population is intended to be general in nature and will be applied at a later date in more computationally intensive studies of processes in individual breaking wave crests.

RELATED PROJECTS

Several potential connections with other proposed projects are being discussed with other investigators. We have an interest in looking at the interface between the model here, where bubbles are treated as a continuous phase, and models which resolve bubbles in the sense of two geometrically distinct phases. We are discussing this problem with Tony Dalrymple (Johns Hopkins), who would like to apply his SPH model to the problem of describing the bubble-resolving problem.

Two possible collaborations with experimentalists are being discussed. Jack Puleo (U. Del.) is proposing to conduct experimental measurements using a combination of sensors measuring reflective and transmitting properties of the water column, together with local conductivity meassurements. Comparison with these experiments would provide a means for evaluating the model's ability to predict the magnitude, vertical distribution and temporal retention of bubbles in the water column. Also, Mick Haller (Oregon State U) is proposing to examine the contribution of bubbles to the apparent foam signature on the water surface following the passage of breaking wave crests, as sensed by video systems such as ARGUS. Comparison with this type of data would allow us to evaluate whether the spatial structure and patchiness of bubble clouds in the water column is being predicted reasonably.

Kirby is a co-PI in MURI effort entitled "Impact of oceanographic variability on acoustic communications". This effort involves the development of a model for spatial and temporal distribution of bubble population under a sea surface with whitecap coverage, for use in water depths in the 50 to 100m range. The development of this model will likely be based on a wave-averaged version of the model developed in this project, which we hope to implement as a component in ROMS.

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PUBLICATIONS

Shi F. and Kirby J. T., 2007, Modeling of surfzone bubbles using a multi-phase VOF model, submitted to 31st International Conference of Coastal Engineering
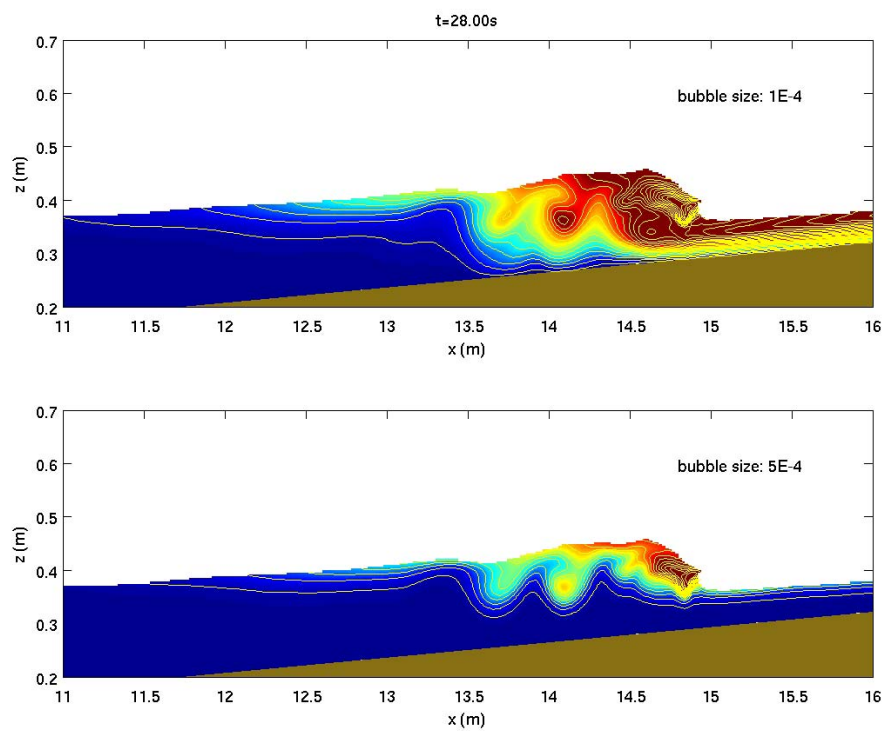

***Figure 1. Bubble concentrations with bubble size 1E-4 m (top)
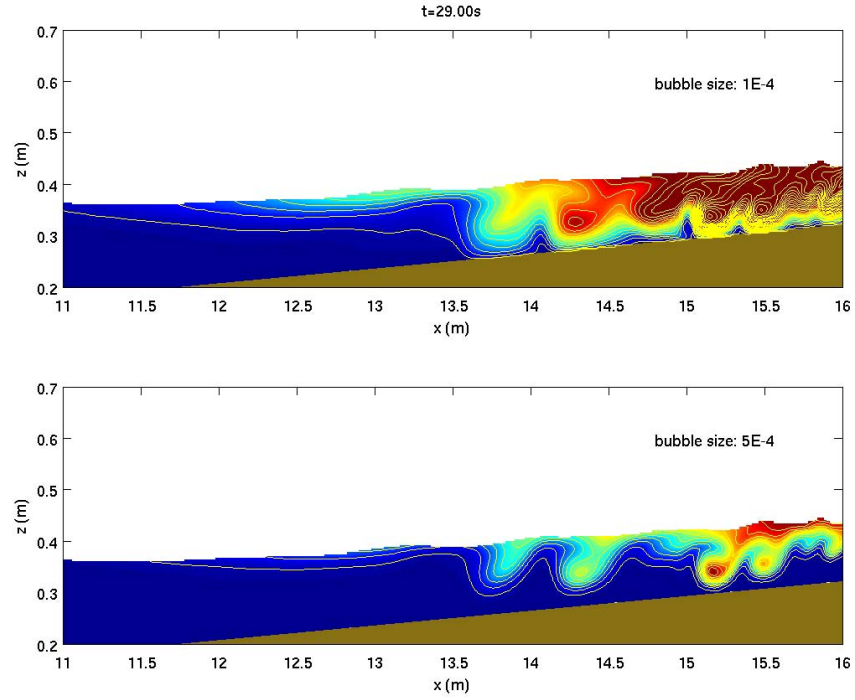and 5 E-4 m (bottom) at t = 28.00s.***

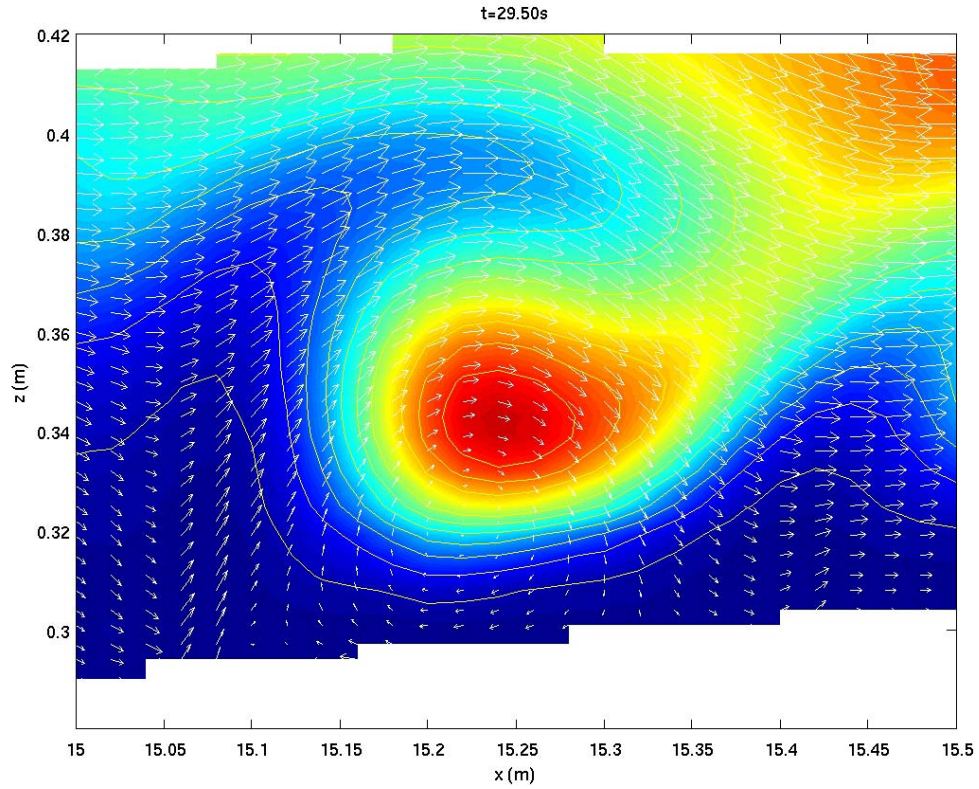*Figure 2. Bubble concentrations with bubble size 1E-4 m (top) and 5 E-4 m (bottom) at t = 29.00s.*

Figure 3. Bubble concentration (color) and water phase velocity (arrows). It is shown that organized eddy motions in the model are successfully trapping and concentrating bubbles towards the central vortex axis.